IEN TIME AND FREQUENCY METROLOGICAL ACTIVITY AND SUPPORT TO USER NEEDS

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Abstract

The increased importance of time and frequency metrology in scientific and industrial applications has raised a request of a wider spectrum of services from the national standard laboratories. On the metrological side, a new generation of frequency standards and the worldwide availability of extremely accurate time dissemination systems have opened new perspectives of research and applications. The IEN Time and Frequency Laboratory, charged with the realization and dissemination of the Italian standard time, in order to meet the requests of different users has been engaged in different activities that are reviewed in this paper, where also the future possibilities are discussed.

INTRODUCTION

The IEN Time and Frequency Laboratory, which has been charged by law in 1991 with the research, realization, and dissemination of the SI unit of time for Italy, has been involved since the seventies in the realization of a local UTC time scale, known as UTC(IEN), and has been contributing with its cesium clocks to the ultimate reference of time UTC established by BIPM. The traceability of UTC(IEN) to the international time scale is realized by two GPS receivers, following the complete BIPM common-view schedule for Europe, and with the software updated according to the technical directives of the CGGTTS Working Group. The dissemination of UTC(IEN) to the real-time user is performed in different ways, as described in the following, with accuracies ranging from 0.05 s to 100 μs.

As regards a major issue coming from the industrial market, that of traceability of secondary standards to the national standard of time and frequency, a variety of solutions are offered through different synchronization techniques, namely coded time signals, passive TV, GPS comparisons, and clock transportation, with uncertainties, at the 1 σ level, ranging from 1×10^{-9} to 5×10^{-14}. Another means of dissemination is the accreditation activity performed by IEN for the Italian Calibration Service (SIT) that has been a response of the National Metrology Institutes (NMI) to the hugely increased request of traceability to the SI units coming from the calibration and test laboratories as a consequence of the implementation in industries of Quality Assurance Standards, such as ISO 9000 series and EN 45001. In this framework, interlaboratory comparisons are organized to check the competence level of the laboratories accredited for frequency and to ensure the traceability to the national standard, therefore completing the Regional Metrological scheme, foreseen to be extended worldwide in the near future, establishing a reliable comparability of measurements, results that will be of great help in removing the technical barriers to the international trade.

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Training courses for technicians, consultation on the development of calibration procedures, and studies on the implementation of the ISO *"Guide to the Expression of Uncertainty in Measurement"* in the field of frequency calibration are also part of the dissemination activity performed. In connection with the implementation of the digital synchronization networks in telecommunications, studies devoted to the statistical characterization of the phase noise effects and of the transferred instabilities in slaved clocks have also been performed.

UTC(IEN) AND TA(IEN) REALIZATION

The national time scale UTC(IEN) is currently realized with five commercial cesium standards, two of which are Hewlett-Packard 5071A of the High Performance type, and the rate of the selected Master Clock is steered to UTC(BIPM), using the internal microstepper, in order to maintain the national reference of time well within $\pm\ 0.5\mu s$ of UTC and to hold the average frequency within $\pm 1 \cdot 10^{-13}$ of the same reference. A noticeable improvement in the compliance to these limits has been obtained since the introduction in 1994 of the new HP cesium clocks in the generation of the IEN time scale. To improve the long-term stability and the reliability of UTC(IEN), an ensemble time algorithm[1] has been implemented since 1995 and the data of the independent atomic time scale TA(IEN) are regularly sent to BIPM.

To evaluate the performances of these two time scales, in Fig. 1 are reported the time differences UTC - UTC(IEN) and TAI - TA(IEN), from BIPM Circulars T, for the period May 1995 – October 1996, with additional information about the Master Clock used and the microstepper correction applied to steer it to UTC. Up to MJD 50169 (27 March 1996), the HP5071 #219 and the HP5061B cesiums were maintained in the clock room with tight temperature and humidity control; the room was abandoned after that date for technical problems of the conditioning system. Since that date, all the clocks have been operating in the Time and Frequency Laboratory, where the environmental changes are more consistent. The mean frequency departures of UTC(IEN) computed from these data were found to be equal to $+0.6 \cdot 10^{-14}$ for 1995 (MJD 49839 to 50079) and to $-1.6 \cdot 10^{-14}$ for 1996 (MJD 50084 to 50384). In Figs. 2 and 3 are shown the frequency instabilities (ADEV) of the two IEN time scales versus UTC and TAI, for observation times from 5 to 160 days, computed with the overlapping sample technique, and in Fig. 4 are reported the mean rates of the IEN clocks versus UTC computed using the Circular T data smoothed with a 30-day moving filter.

Looking at the results obtained in the IEN time scales, the following considerations can be made. Even if the new cesium clocks give a significant improvement on the long-term stability, instabilities of a few units in 10^{-14} can still be detected, causing trouble in achieving the goal of a synchronization at 100 ns with respect to UTC. By an inspection of Fig. 4, it appears that in the second half of 1996, in correspondance with the removal of the clocks from the dedicated room, a small but appreciable increase of the instability is observable, mostly due to the variation of temperature, which causes also a certain correlation among clocks. But some sudden frequency variations were detected on a 5071A cesium even in the controlled environmental situation, as seen in the first part of Fig. 4. Similar anomalies have been observed also by other laboratories. This makes difficult the modelling of clock performances and, thus, their correct prediction. Such aspect requires further investigation.

The following improvements in the time scale realization are expected. First, the move of the clocks in a new temperature-controlled room near to the Time and Frequency Lab, and the addition of a third HP5071A cesium in the ensemble. Second, an optical fiber link is foreseen connecting with the Italian telecommunication research center (CSELT), located about 10 km from IEN. This connection would guarantee the safe introduction of the two HP5071A

clocks available at CSELT, thus increasing the number of new generation clocks realizing the national time scale. Due to these changes in the ensemble, also some modification in the algorithm seems advisable. Particularly the weighting procedure, now based on the observation of one year of data to detect the largest seasonal fluctuation, is probably to be changed by the introduction of an exponential moving average, better suited to estimate the current clock behavior and giving less importance to older data. By the modelling of the long-term frequency variations, also the adaptation of the frequency prediction techniques will be investigated.

INTERNATIONAL TIME TRANSFERS

An average of 45 GPS common-view comparisons are routinely performed daily to relate UTC(IEN) to the international time scale UTC, and the IEN results are also compared weekly with those of the Physikalisch-Technische Bundesanstalt (PTB) - Germany and of the Institute of Radio Engineering and Electronics (IREE-TP) - Czech Republic. The availability of two GPS receivers of different manufacturers in these laboratories has given us the chance to investigate in 1995 the noise limits of this synchronization system and the long-term stability of the equipment used, both using the BIPM regular common-view schedule and a special one featuring equally spaced tracks with high-elevation-angle satellites.

The results, reported in [2], showed a time deviation over 1 hour of less than 2 ns for the link between IEN and IREE, but also the presence of daily variations of several nanoseconds that could be related to the sensitivity of the receiving antennas and down-converters to outdoor temperature variations, and also to the use of a rough model for the computation of the ionospheric correction inside the receivers. The long-term behavior of the two receivers at IEN had been already investigated over more than one year, in 1993 and in 1994, averaging the daily synchronization results versus GPS time of each receiver and computing their differential delay; a peak-to-peak variation of 5 ns and a correlation between the differential delay and the outdoor temperature was found.

On the other end, the delay of the NBS/GPS reference receiver of IEN, calibrated by BIPM at the end of January 1995 by means of a portable reference GPS receiver, was found in good agreement (–20 ns vs. –18 ns) with a previous calibration performed in 1986.[3]

From October to December 1995, IEN joined the international synchronization experiment based on INTELSAT satellites at 307°, using a Direct Broadcasting Satellite receiving station and a MITREX modem, to test the frequency and time transfer capability of such systems used in a one-way mode.[4] In the final setup, the satellite beacon frequency was used as a reference to lock an oscillator of the conversion chain to compensate for the Low Noise Converter oscillator drift that would have exceeded the tight input frequency tolerances of the modem used. The one-way synchronization measurements were performed during the 300 s range phase that preceeded the European two-way sessions, using the range data from three laboratories to correct for the satellite position delays.

As a sample of the receiving system performances, in Fig. 5 are reported for the link IEN-NPL the frequency and time instability estimators MDEV and TDEV, for integration times between 1 s and 2000 s, after the satellite movement has been modelled with a fifth-order polynomial regression. In Fig. 6 we have reported the comparisons between the time scales of IEN and of the Technical University of Graz (TUG) from 6 to 29 November 1995, as obtained by the one-way INTELSAT measurements corrected with the range data, and by GPS common view. The standard deviation of the residuals between the two synchronization systems is 4 ns.

In order to join the two-way network, that will start its regular schedule again next year, a VSAT

(Very Small Aperture Terminal) RF Transceiver designed for a two-way satellite communication system and operating in the whole Ku-band frequency range (14.0 - 14.5 GHz Tx, and 10.95 - 12.75 GHz Rx) has been installed in September 1996 near the Time and Frequency Laboratory. The system is equipped with a 1.8 m dish antenna, a 4 W High Power Amplifier, and a Low Noise Amplifier with a noise temperature of 110 K and a frequency agility of 1 kHz in the transmitting and receiving chains. A bench testing, using MITREX codes, of the delay instabilities of this equipment (Tx plus Rx) for different signal-to-noise ratios (C/N), supplying to the receiving part the transmitted RF signal converted by a local mixer and synthesizer, has been performed and the results are reported in Fig. 7. For the three typical simulated C/N values, a $\tau^{-3/2}$ slope is shown for MDEV and an uncertainty limit of the order of $1{\cdot}10^{-13}$ over 500 s is reached by the system. It is planned to have this station operative in the first half of 1997, after receiving approval from the national INTELSAT signatory.

UTC(IEN) DISSEMINATION SOURCES

The dissemination in real time of UTC(IEN) to the Italian users is performed by means of dedicated services available through the reception of the regular programs broadcasted by the national broadcasting company (RAI), by a time-coded information distributed on the telephone network, and by the synchronization of two NTP (Network Time Protocol) primary servers. The coded time signals generated by IEN and broadcasted 15-25 times per day by the RAI FM and AM transmitters, apart from being the most common source of the time of the day information in Italy, can be used both for the synchronization of remote clocks with a precision of the order of 0.1 ms and for disciplining the frequency of quartz oscillators at the level of $1{\cdot}10^{-9}$.[5] Also, the time of the day announcement service made by the Italian Telecom is synchronized by these signals.

Fig. 8 shows the format of the RAI time code (SRC), updated in 1995 to include the information on the current year and warnings about the switching from standard to daylight saving time and the introduction of a leap second on UTC time scales. The coded time signals transmitted from the RAI studios in Rome are continuously monitored at IEN to check the propagation delays and to compare the controlled clocks of some users. A sample of the long-term behavior of this delay is given in Fig. 9, reporting the results obtained from August to October 1996, where it can be seen that the majority of the data is within a range of 0.1 ms. The coded time and date information (CTD) service on telephone lines, following the format agreed in 1991 among some European laboratories, is addressed mainly to the synchronization of PC clocks and has been operative at IEN since 1991.[6] This service is operated by several European timekeeping laboratories, mostly with the capability of round-trip delay determination, a feature that has not been implemented in our case. A set of three time-code generators provides the redundancy of the system that cannot be accessed from abroad.

To provide an average compensation of the delay at the user side, the 1 pps reference in the code (transition from carriage return to line feed characters) is anticipated by 70 ms. An investigation on the effective propagation delays at different distances and on the synchronization precision obtainable has been recently performed using a Time Code Generator and an On Time Marker (OTM) monitor, both developed at the Technical University of Graz. To estimate the half-round trip delay, the GDM (Generator Delay Measurement) function of the generator and dedicated software were used and, when possible, the time of arrival of the code time reference (OTM) has been measured versus UTC(IEN) with an external time-interval counter. The GDM results are averaged over 8 consecutive measurements, while the OTM ones are averaged over 50 samples. The tests were performed in different laboratories: at IEN, receiving the signal back

through the local telephone exchange or connecting to the services of other countries (Austria - TUG, Germany - PTB, the Netherlands - VSL, Portugal - IPQ, and Switzerland - OFMET) and in other Italian institutions (Cagliari Observatory in Sardinia, Hewlett-Packard Italy - Milan, Vitrociset - Rome) that are synchronized to the IEN time scale.

In Fig. 10 are reported the half-round trip results obtained in the GDM mode and, in the case of the IEN local link and of the Hewlett-Packard one, also the calibration of the one-way (OTM) delay. For the other connections, where only 4 synchronizations were available; the results are reported in Table 1. One can observe in all cases a residual time offset between the OTM and the GDM evaluation ranging from 2 to 7 ms inside the national network, with outliers of more than 10 ms for international calls. The standard deviation over different calls from the same location has been of the order of 1-2 ms. Looking to the average delays found, the 70 ms advance given to the IEN CTD time marker allows synchronization inside the country, even without a calibration of the path delay, within ±20 ms.

A final consideration that can be made is that the modem delays and their asymmetry are more influential than the geographical distance in the synchronization error. The time of the day, synchronized by the IEN standard signals, and general information about the activity of the Time and Frequency Lab can be accessed via the World Wide Web at the address "www.ien.it". Moreover, two NTP primary servers located in the IEN buildings are directly synchronized by the CTD time reference previously described. This last service can be accessed via the Internet at the following server addresses: "time.ien.it" and "tempo.cstv.to.cnr.it".

TRACEABILITY TO UTC(IEN)

In the framework of the Italian Calibration Service SIT, the IEN has already accredited 16 laboratories for frequency and performs the remote calibration of their reference oscillators using a variety of synchronization methods, depending on the uncertainty level requested. In a similar way, the traceability to the national time scale is also guaranteed to some 15 other metrological laboratories. The uncertainty levels recognized to the accredited centers can range from $1 \cdot 10^{-9}$ to $3 \cdot 10^{-13}$, depending on the reference oscillator and on the synchronization system used. In Fig. 11 is shown a sample over a three-month period of the calibration data of a remote disciplined quartz oscillator. In this case, the synchronization and disciplining system used, based on the IEN/RAI coded time signals, ensures the removal of the frequency drift and a traceability to UTC(IEN) within a few parts in 10^{-10}. The traceability to the IEN time scale is also obtainable using the GPS signals, either with the common-view technique or using a kind of "melting pot" technique that is especially suited to the multichannel receivers found in disciplined devices.[7]

The characterization of this type of receiver is of particular interest also for its possible use in the primary laboratories as an alternative to the more expensive and not very reliable timing receiver presently on the market. A sample of the uncertainty obtained in the frequency calibration of a remote HP5071A clock using a GPS multichannel receiver on the user side, and the reference receiver at IEN, can be seen in Fig. 12. The daily time differences between UTC(IEN) and UTC(Lab), obtained computing a mean value from the 24 series of 100 s measurements at the remote site and from the average of all the measurement collected at IEN according to the common-view schedule, have been used to compute each data point. The standard deviation level obtained, using a 5-day moving average filter, is of the order of $5 \cdot 10^{-14}$. Finally, concerning the well-known passive television method that is still used in 50% of the Italian laboratories, an example of the capability (ADEV) of the system used in common view between IEN and CSELT laboratories (10 km) to compare two HP5071A High

Performance standards is shown in Fig. 13. These results, that have been obtained computing the time differences between 60 measurements one second apart, repeated at both sides every 2 minutes, with improved TV receivers and sync separators developed by CSELT, demonstrate that the noise level of such arrangement after 1 day reaches the nominal noise level due to the clocks compared.

STATISTICAL PROBLEMS IN TELECOMMUNICATIONS AND INDUSTRIAL APPLICATIONS

The expertise gained in statistics and mathematical modelling in time and frequency metrology has found some important applications for different industrial needs. Firstly, IEN has been charged by the Italian telecommunication research center (CSELT) to investigate on the stability characteristics of clocks to be used in the Synchronous Digital Hierarchy. The investigation, either on theoretical aspects or in experimental evaluations, allowed the clarification of the relationships among the different families of statistical tools used to specify clock stability (power spectra, variances, peak-to-peak behavior) and the evaluation of the transfer of noises along a chain of phase-locked clocks.[8,9]

A second activity concerned the implementation of the ISO *"Guide to the Expression of Uncertainty in Measurement."* Recently IEN was charged by the EAL Task Force revising WECC Doc. 19 to prepare some examples of uncertainty evaluation in time and frequency. Therefore, two procedures taken among the typical measurement problems of time and frequency calibration laboratories were developed[10] and will be used also in support to the Italian calibration service. On such a subject IEN launched also a EUROMET proposal (#382/1996). On a contract given by an Italian high-technology industry, IEN studied also the possibility of estimating the optimal calibration interval of a measuring instrument by using suitable stochastic models. Calibration error may be in fact one of the most important sources of measurement errors but, on the other hand, calibrations have an overall cost and may imply an interruption of the production process. Using the theory of stochastic processes and time series analysis, some suitable models have been developed that seemed promising after a preliminary experimental validation.[11] Due to the qualification gained in this field, an IEN researcher was called to work as expert in the ISO Technical Committee 176 dealing with standardization of suitable procedures (also in measurements) to assure quality programs.

CONCLUSIONS

The IEN time and frequency metrological activities cover a wide range of the needs of Italian users in research, traceability, and standardization. To improve the accuracy, stability, and reliability of UTC(IEN) realization and dissemination, a number of actions are going to be undertaken, such as the research on a cesium fountain primary standard, the increase of the number of new cesium standards, and the realization of new standard signals distribution links and equipment. The use of higher resolution measurement systems, more frequent clocks intercomparisons, and security systems on the reference frequency and time signals are also foreseen. Concerning the time comparisons systems, the two-way station will be put in operation and studies on the accuracy of GPS receivers will be carried out. A very consistent increase of the accreditation activity is also expected in the near future and, finally, a database of the relevant measurement results performed will be made available to the user through electronic mail.

mail.

ACKNOWLEDGMENTS

The authors wish to thank the following people and institutions for their very helpful cooperation: D. Kirchner and H. Ressler (Technical University of Graz, Austria), D. Beretta (Hewlett-Packard, Italy), L. Mureddu (Cagliari Observatory, Italy), D. Tonti (Vitrociset, Italy), and the colleague S. Denasi.

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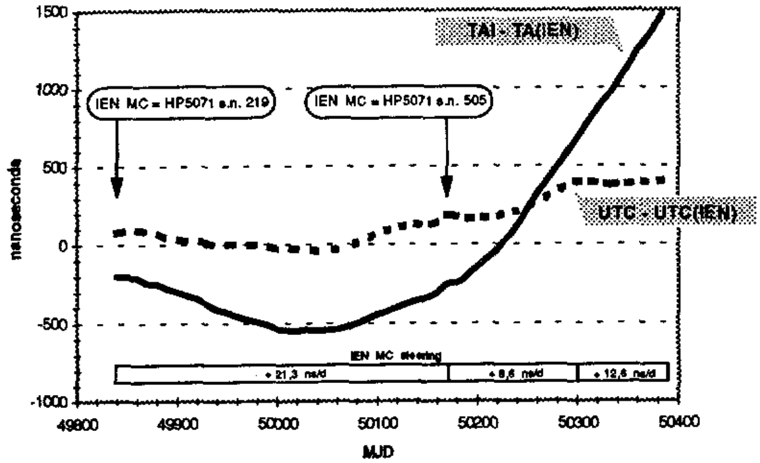


Fig. 1 - UTC(IEN) and TA(IEN) from May 1995 to October 1996 (MJD: 49839 - 50384) - BIPM Circular T

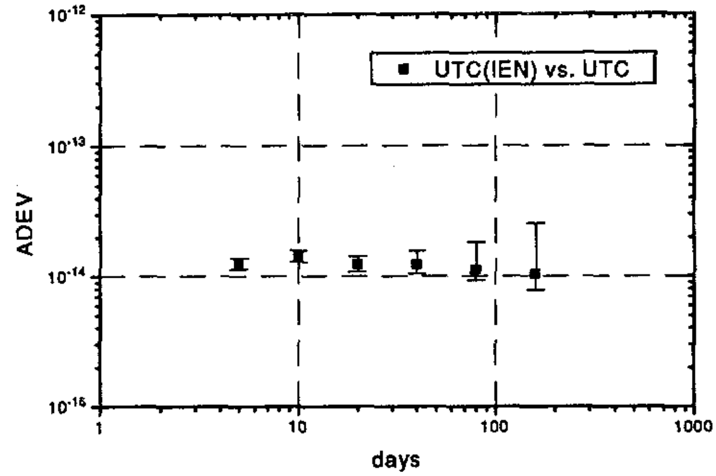


Fig. 2 - Frequency instability of UTC(IEN) vs. UTC from May 1995 to October 1996 - BIPM Circular T

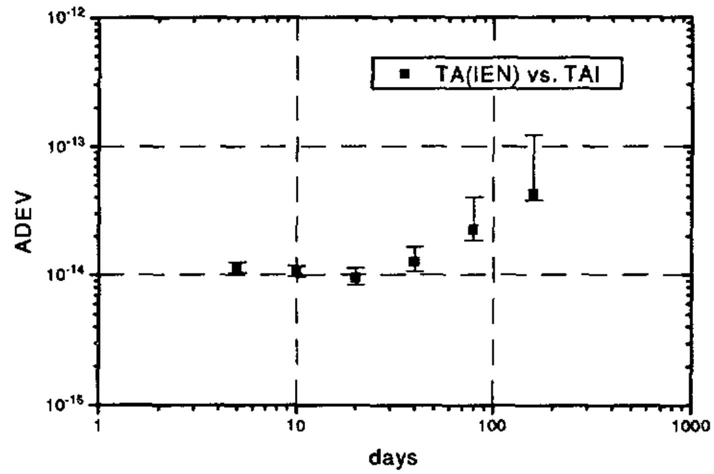


Fig. 3 - Frequency instability of TA(IEN) vs. TAI from May 1995 to October 1996 - BIPM Circular T

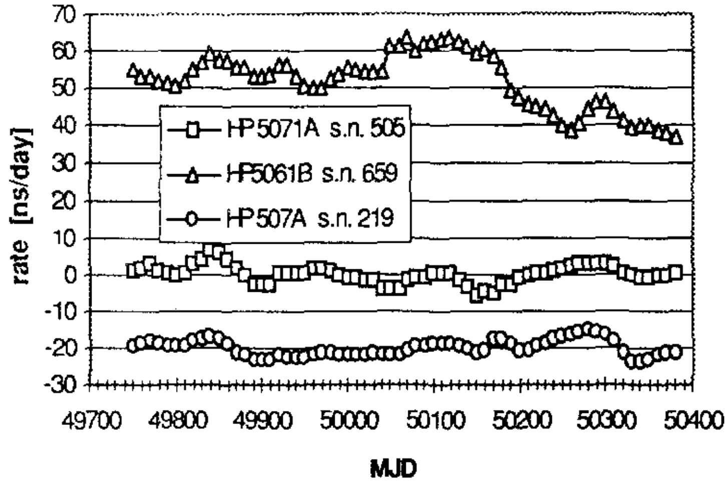


Fig. 4 - Rates of the IEN cesium clocks vs. UTC from January 1995 to October 1996

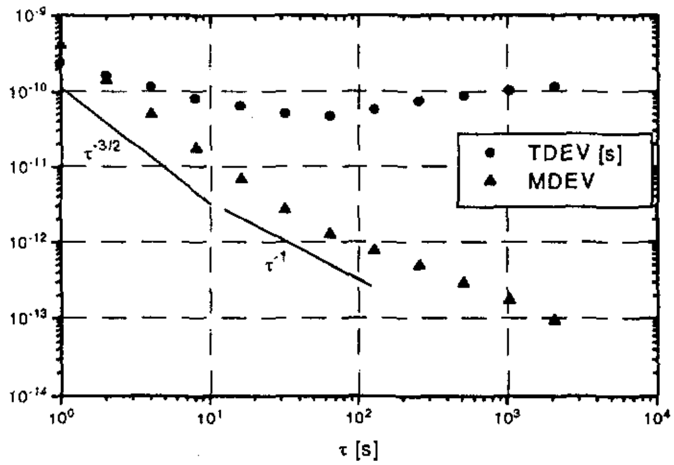


Fig. 5 - IEN / NPL synchronization link instabilities

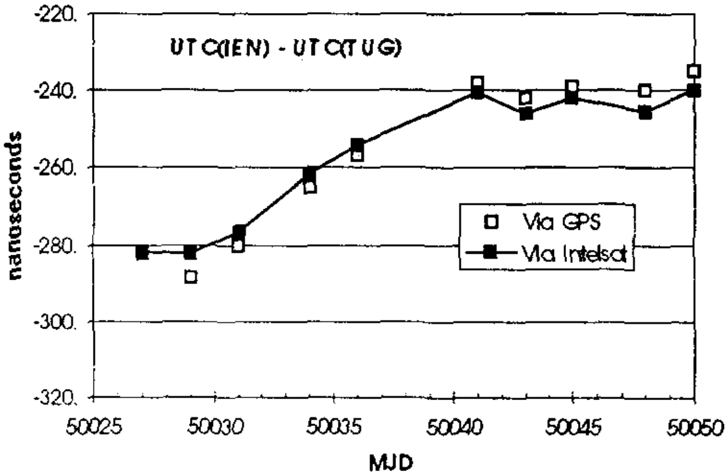


Fig. 6 - IEN / TUG time scales comparisons

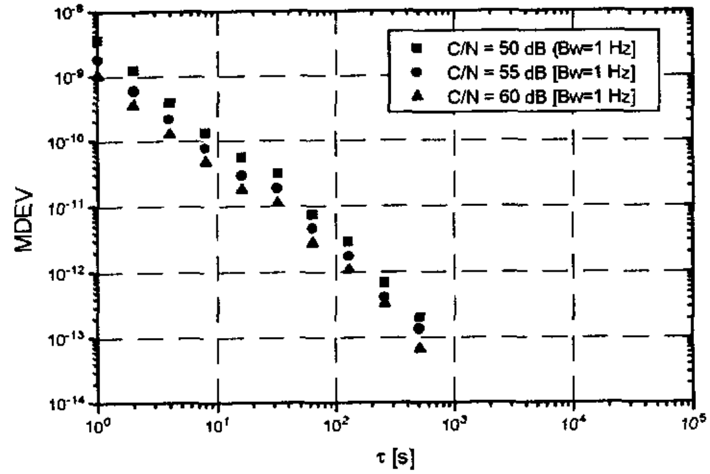


Fig. 7 - IEN two-way station instability for different signal to noise ratios

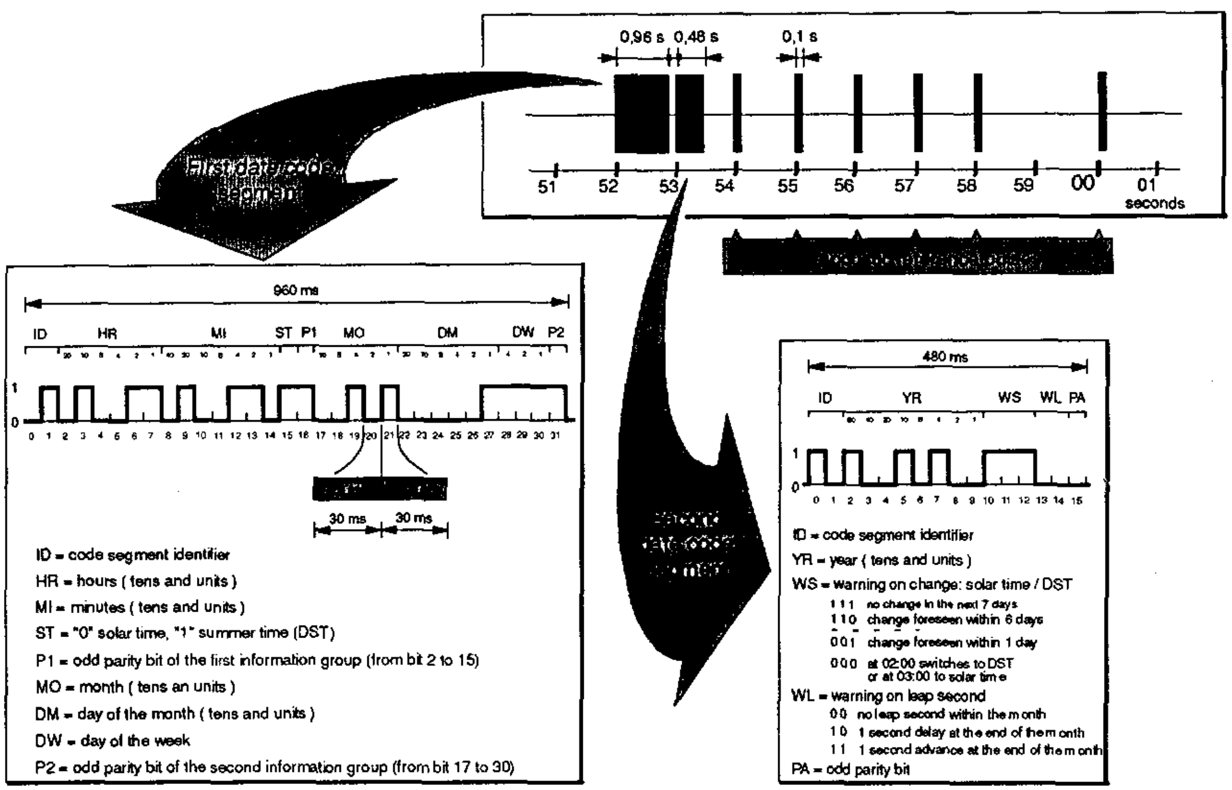
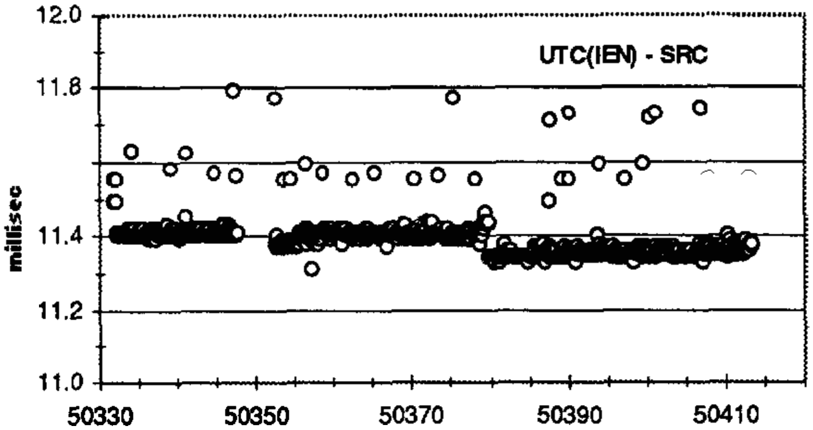
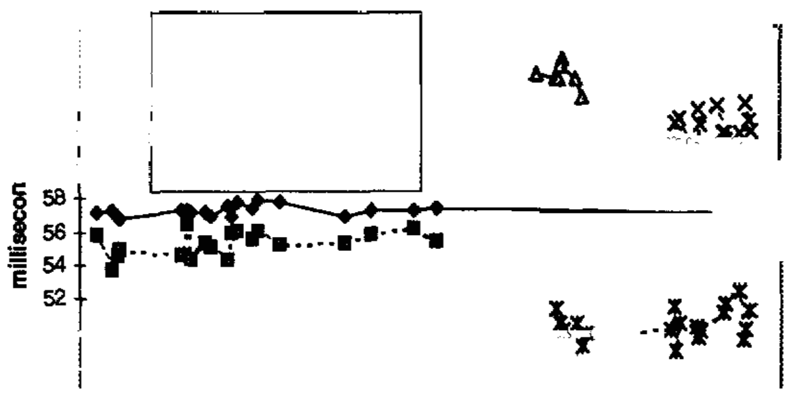


Fig. 8 - IEN / RAI Time Code format





Lab.	OTM	σ(mean)	σ(single)	GDM	σ(mean)	σ(single)	OTM-GDM	Distance
	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[km]
IEN(I)	57.3	0.3	2.4 - 2.6	55.3	0.5	0.9 - 1.5	2.0	-
CAO(I)	-	-	-	83.8	1.5	1.3 - 1.8	-	650

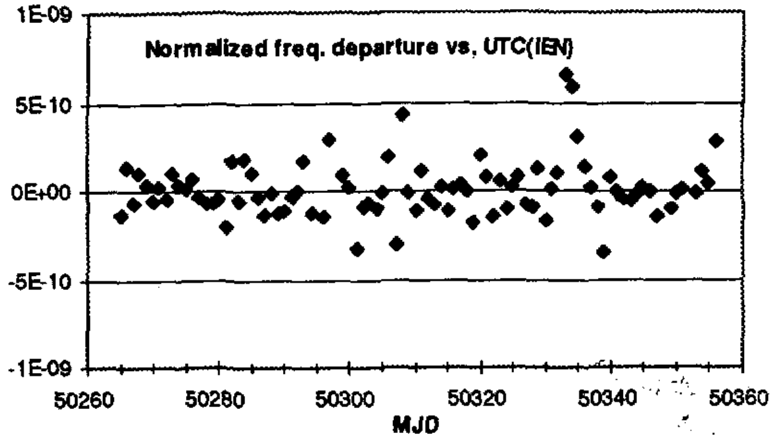


Fig. 11 - Ovenized quartz oscillator disciplined by IEN / RAI time signals

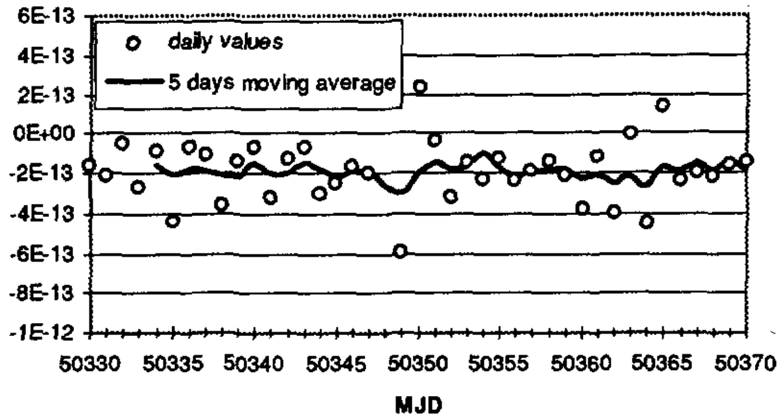


Fig. 12 - Frequency calibration of a remote cesium using a GPS multichannel receiver

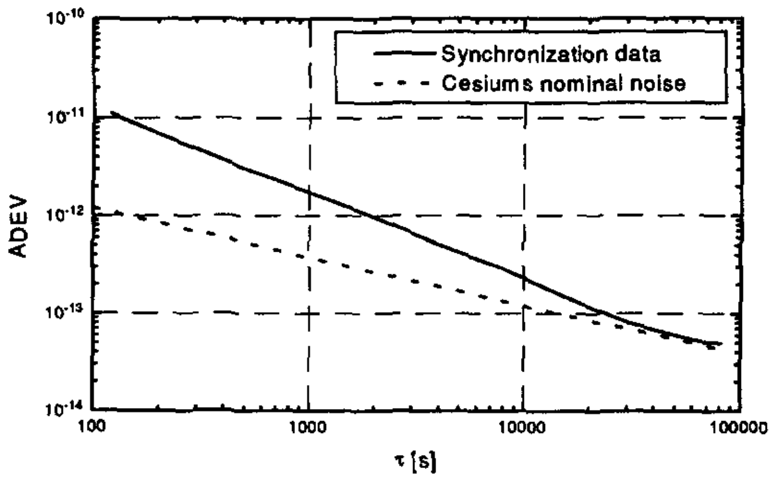


Fig. 13 - Frequency instability of two cesium clocks compared via the passive TV method in common-view

Questions and Answers

DAVID ALLAN (ALLAN'S TIME): Two quick questions on the chart you have showing the frequency performance of the 5071s. Can you show that chart quickly?

FRANCO CORDARA: Yes.

DAVID ALLAN: First question is what is the reference? Second question, there appears to be the correlation of the two, has that been correlated with an environmental parameter? Temperature, humidity, pressure?

FRANCO CORDARA: The reference chosen has been UTC, because I think it was the best reference in our case. And the correlation that can be seen here on the three standards is due to the fact that the temperature in the normal time and frequency lab has been changed this summer and fall by 3 degrees. And it has seasonal changes which are voluntarily performed in the lab. And, of course, the temperature is not stable within 1 degree and they have 2 degrees.

We have noticed from the temperature recordings that these were corresponding to about 3-degree variations. And here to lowering of the same temperature.